

# Tetra-quark mesons with exotic quantum numbers\*

## – Their production and related –

Kunihiko Terasaki

*Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan  
Institute for Theoretical Physics, Kanazawa University, Kanazawa 920-1192, Japan*

Tetra-quark mesons with exotic quantum numbers and their production rates are studied.

Tetra-quark mesons can be classified into the following four groups [1] (and [2]),

$$\{qq\bar{q}\bar{q}\} = [qq][\bar{q}\bar{q}] \oplus (qq)(\bar{q}\bar{q}) \oplus \{[qq](\bar{q}\bar{q}) \oplus (qq)[\bar{q}\bar{q}]\} \quad (1)$$

with  $q = u, d, s$  (and  $c$ ), where parentheses and square brackets denote symmetry and anti-symmetry, respectively, of flavor wavefunctions (wfs.) under exchange of flavors between them. Each term in the right-hand-side of Eq. (1) is again classified into two groups with  $\bar{\mathbf{3}}_c \times \mathbf{3}_c$  and  $\mathbf{6}_c \times \bar{\mathbf{6}}_c$  of the color  $SU_c(3)$  [1]. In the case of heavy mesons, the  $\bar{\mathbf{3}}_c \times \mathbf{3}_c$  state is taken as the (dominant part of) lower lying one [3, 4]. Then, spin ( $J$ ) and parity ( $P$ ) of corresponding  $[qq][\bar{q}\bar{q}]$  and  $[qq](\bar{q}\bar{q}) \pm (qq)[\bar{q}\bar{q}]$  mesons are  $J^P = 0^+$  and  $1^+$ , respectively. However, we ignore  $(qq)(\bar{q}\bar{q})$  [5], although still controversial [6].

One of candidates of heavy tetra-quark mesons is  $D_{s0}^+(2317)$ . It was discovered in the  $D_s^+\pi^0$  mass distribution, while no signal in the  $D_s^{*+}\gamma$  channel in inclusive  $e^+e^-$  annihilation [7, 8]. This fact suggests that the decay  $D_{s0}^+ \rightarrow D_s^+\pi^0$  is dominant and caused by the isospin conserving strong interaction, because of the well-known hierarchy of hadron interactions [4],  $|\text{isospin conserving strong ones}| \gg |\text{electromagnetic ones}| \gg |\text{isospin non-conserving ones}|$ . Here the last one is of the order of  $\alpha$  [9], where  $\alpha$  is the fine structure constant. Therefore,  $D_{s0}^+(2317)$  should be an iso-triplet state, and hence it is natural to assign  $D_{s0}^+(2317)$  to  $\hat{F}_I^+ \sim [cn][\bar{s}\bar{n}]_{I=1}$ , ( $n = u, d$ ) [2]. In this case, the observed narrow width [10] of  $D_{s0}^+(2317)$  is understood by a small overlap of color and spin wfs. [3, 4, 11]. The above assignment is consistent [5, 12, 13] with the observation in  $B$  decays [14],  $Br(B \rightarrow \bar{D}\bar{D}_{s0}^+(2317)[D_s^+\pi^0]) = (8.5_{-1.9}^{+2.1} \pm 2.6) \times 10^{-4}$  and  $Br(B \rightarrow \bar{D}\bar{D}_{s0}^+(2317)[D_s^{*+}\gamma]) = (2.5_{-1.8}^{+2.0} (< 7.5)) \times 10^{-4}$ , where signals observed in the  $D_s^+\pi^0$  and  $D_s^{*+}\gamma$  are denoted as  $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$  and  $\tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]$ , respectively. Therefore,  $\hat{F}_I^+$  and its iso-singlet partner  $\hat{F}_0^+ \sim [cn][\bar{s}\bar{n}]_{I=0}$  are identified with  $\tilde{D}_{s0}^+(2317)[D_s^+\pi^0]$  and  $\tilde{D}_{s0}^+(2317)[D_s^{*+}\gamma]$ , respectively, because the former decays dominantly into the  $D_s^+\pi^0$  state while the latter into the  $D_s^{*+}\gamma$  due to the above hierarchy of hadron interactions. For more details, see Refs. [2], [4], [5] and [11].

Another candidate of tetra-quark meson is  $X(3872)$  with  $J^{PC} = 1^{++}$ , where  $C$  is the charge conjugation parity. It was discovered [15] and confirmed [16] in the  $\pi^+\pi^-J/\psi$  mass distribution. However, the  $X(3872) \rightarrow \pi^+\pi^-J/\psi$  decay violates badly isospin conservation [17, 18] which works well in ordinary strong interactions. Such a large violation of isospin symmetry can be understood [19] by the  $\omega\rho^0$  mixing which is well-known as the origin of isospin non-conservation in nuclear forces [20], because the  $\rho^0$  pole contribution is enhanced in the  $X(3872) \rightarrow \pi^+\pi^-J/\psi$  decay due to  $|m_\omega - m_\rho| \ll |m_\omega|$ . In fact, the measured values of the ratio of decay rates

$$R^\gamma \equiv \frac{Br(X(3872) \rightarrow \gamma J/\psi)}{Br(X(3872) \rightarrow \pi^+\pi^-J/\psi)} = \begin{cases} 0.14 \pm 0.05, & (\text{Belle [17]}) \\ 0.33 \pm 0.12, & (\text{Babar [21]}) \end{cases} \quad (2)$$

have been approximately reproduced, i.e.,  $(R^\gamma)_{\text{tetra}} \simeq (R^\gamma)_{\text{Babar}} \simeq (R^\gamma)_{\text{Belle}}$  [5, 19], by assuming that  $X(3872)$  is a tetra-quark system like a  $\{[cn](\bar{c}\bar{n}) + (cn)[\bar{c}\bar{n}]\}_{I=0}$  meson [22] (or a  $D^0\bar{D}^{*0}$  molecule [23]) and that the isospin non-conservation under consideration is caused by the  $\omega\rho^0$  mixing. In contrast, if  $X(3872)$  were assumed to be a charmonium  $X_{c\bar{c}}$  with  $J^{PC} = 1^{++}$ , the above ratio could not be reproduced, i.e.,  $(R^\gamma)_{c\bar{c}} \gg (R^\gamma)_{\text{Babar}} \simeq (R^\gamma)_{\text{Belle}}$  [5, 19]. Therefore, we have seen that a tetra-quark interpretation of  $X(3872)$  is favored over the charmonium. In addition, production [24] of the *prompt*  $X(3872)$  seems to favor a compact object like a tetra-quark meson over an extended object like a loosely bound molecule [25], and hence the tetra-quark model mentioned above survives while the  $D^0\bar{D}^{*0}$  molecular model would be ruled out.

Although quantum numbers of  $D_{s0}^+(2317)$  and  $X(3872)$  are not exotic, their tetra-quark interpretation has been favored by experiments as seen above, so that existence of their partners with exotic quantum numbers is expected. However, for example, neutral and doubly charged partners,  $\hat{F}_I^0$  and  $\hat{F}_I^{++}$ , of  $\hat{F}_I^+ = D_{s0}^+(2317)$  have not been observed in inclusive  $e^+e^-$  annihilation [26]. Nevertheless, it does not necessarily imply their non-existence but it might suggest

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that their production is suppressed in this process. This can be understood by considering their production in the framework of minimal  $q\bar{q}$  pair creation [13]. On the other hand, their production rates in  $B$  decays have been very crudely estimated as  $Br(B_u^+ \rightarrow D^- \hat{F}_I^{++}) \sim Br(B_d^0 \rightarrow \bar{D}^0 \hat{F}_I^0) \sim Br(B_u^+(B_d^0) \rightarrow \bar{D}^0(D^-) \hat{F}_0^+) \sim Br(B_u^+(B_d^0) \rightarrow \bar{D}^0(D^-) \hat{F}_I^+)_{\text{exp}} \sim 10^{-(4-3)}$ , because the above decays are described by the same type of quark-line diagrams and hence the sizes of their amplitudes are expected to be nearly equal to each other [12, 13, 27].

Observations of mesons with exotic quantum number(s) provide additional evidences for existence of tetra-quark mesons. In our scheme,  $\hat{E}^0 \sim [cs][\bar{u}\bar{d}]$  meson [2] is only one scalar meson with  $C = -S = +1$ . Axial-vector mesons with exotic quantum numbers, which come from  $\{[qq](\bar{q}\bar{q}) \oplus (qq)[\bar{q}\bar{q}]\}$ , are  $H_{Acc}^+ \sim (cc)[\bar{u}\bar{d}]$  with  $C = 2, S = 0, I = 0$ ;  $K_{Acc} \sim (cc)[\bar{n}\bar{s}]$  with  $C = 2, S = 1, I = 1/2$ ;  $E_{A(cs)}^0 \sim (cs)[\bar{u}\bar{d}]$  with  $C = 1, S = -1, I = 0$ ;  $E_{A[cs]} \sim [cs](\bar{n}\bar{n})$  with  $C = 1, S = -1, I = 1$ . Their masses can be very crudely estimated as  $m_{\hat{E}^0} \simeq 2.32$  GeV,  $m_{H_{Acc}} \simeq 3.87$  GeV,  $m_{K_{Acc}} \simeq 3.97$  GeV,  $m_{E_{A(cs)}} \simeq m_{E_{A[cs]}} \simeq 2.97$  GeV by using a quark counting with  $m_c - m_s \simeq 1.0$  GeV and  $m_s - m_n \simeq 0.1$  GeV as in Ref. [28], where  $m_{D_{s0}(2317)} \simeq 2317$  MeV and  $m_{X(3872)} \simeq 3872$  MeV have been taken as the input data. It should be noted that we have predicted [28] the mass of hidden-charm iso-triplet scalar  $\hat{\delta}_{I=1}^c$  to be  $m_{\hat{\delta}_{I=1}^c} \simeq 3.3$  GeV, using the same quark counting, and that the result fits much better to a peak at 3.2 GeV in the  $\eta\pi$  channel, which was observed by the Belle [29] and can be considered as a signal of  $\hat{\delta}_{I=1}^c$ , than predictions of the corresponding meson mass by the other models [30, 31].

Production of tetra-quark mesons is now in order. Productions of  $K_{Acc}^+$  and  $K_{Acc}^{++}$  can be described by the quark-line diagram, Fig. 1(c), which is of the same type as Fig. 2(a) and Fig. 3(b) in Ref. [27] describing  $B_u^+ \rightarrow \bar{D}^0 \hat{F}_I^+$  and  $B_d^0 \rightarrow D^- \hat{F}_I^+$ , respectively. Because  $Br(B_u^+(B_d^0) \rightarrow \bar{D}^0(D^-) D_{s0}^+(2317))_{\text{exp}} \sim 10^{-(4-3)}$  as mentioned before, production rates for  $K_{Acc}^+$  and  $K_{Acc}^{++}$  would be very crudely estimated as

$$Br(B_c^+ \rightarrow D^{*-} K_{Acc}^{++}) \sim Br(B_c^+ \rightarrow \bar{D}^{*0} K_{Acc}^+) \sim 10^{-(4-3)}, \quad (3)$$

because differences of kinematics between  $B_n$  and  $B_c$  decays under consideration do not change order of magnitude of their branching fractions [32]. Production of  $H_{Acc}^+$  is described by the diagram Fig. 1(d) which describes the CKM suppressed decay, so that the rate for  $H_{Acc}^+$  production would be more suppressed by a factor  $\sim |V_{cd}/V_{cs}|^2 \simeq 0.05$  than the above ones, where  $V_{cd}$  and  $V_{cs}$  are the CKM matrix elements, although it is described by the same type of diagram as the previous ones. Productions of scalar and axial-vector tetra-quark mesons with  $C = -S = 1$  can be described by the diagrams, (a) and (b) in Fig. 1. These diagrams are of the same type as that of Fig. 4(c) in Ref. [27] describing  $\bar{B}_d^0 \rightarrow K^- \hat{F}_I^+$  whose rate has already been measured [33]. However, the result is smaller by about an order of magnitude than  $Br(\bar{B}_d^0 \rightarrow D^- D_{s0}^+(2317))_{\text{exp}}$  because the former includes an  $s\bar{s}$  pair creation, as discussed in Refs. [27] and [32]. In contrast, we now expect that rates for decays described by the diagrams (a) and (b) in Fig. 1 are not suppressed, because these diagrams involve no  $s\bar{s}$  creation, i.e.,

$$\begin{aligned} Br(B_u^- \rightarrow D^{*-} E_{A(cs)}^0) &\sim Br(B_u^- \rightarrow D^{*-} E_{A[cs]}^0) \sim Br(B_u^- \rightarrow D^- \hat{E}^0) \\ &\sim Br(\bar{B}_d^0 \rightarrow \bar{D}^{*0} E_{A(cs)}^0) \sim Br(\bar{B}_d^0 \rightarrow \bar{D}^{*0} E_{A[cs]}^0) \sim Br(\bar{B}_d^0 \rightarrow \bar{D}^0 \hat{E}^0) \\ &\sim 10 \times Br(\bar{B}_d^0 \rightarrow K^- D_{s0}^+(2317)) \sim 10^{-(4-3)}. \end{aligned} \quad (4)$$

Although decay properties of these exotic mesons would be useful to search for them, rates for two- and body-decays of, in particular,  $K_{Acc}$  and  $H_{Acc}^+$  would be crucially sensitive to their mass values because they are estimated to be very close to their corresponding thresholds. Therefore, calculations of these rates would be keenly model dependent at the present stage. In addition, no experimental data which can be used as the input data is known, so that they are left as one of our future subjects.

In summary, we have studied scalar and axial-vector mesons with exotic quantum numbers, and have estimated their production rates, comparing quark-line diagrams describing their productions with those of  $D_{s0}^+(2317)$ . As the result, we have seen that a major part of them can be large enough to be observed in  $B$  decays.

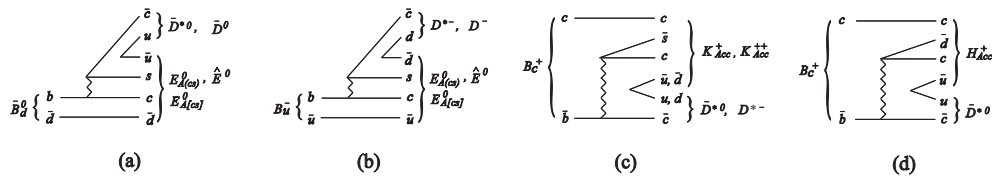


Fig. 1: Productions of tetra-quark scalar and axial-vector mesons with exotic quantum numbers.

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